Lattice-Automaton Modelling of Bioturbation and Benthic Activity

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LONG-TERM GOALS

The long term goal is a quantitative and mechanistic understanding of the relationship between infaunal ecology, in the form of animal actions and rates, and the consequent modification of sediments, including the creation and destruction of heterogeneities and the modes and rates of sediment component mixing.

OBJECTIVES

The development of a model-computer code, i.e., the lattice-automaton model, that embraces the discrete nature of sediments and organisms, rather than averaging it away, and that utilizes biologically relevant parameters, such as animal sizes, population density, feeding and locomotion rates, and probabilities for observed behaviour(s), to drive the model and produce predictions about sediment composition and fabric.

APPROACH

My approach is the direct modelling of organism-sediment interactions via a new type of model. Biologically active sediment is represented on a computer as a regular lattice of quasi-particles with individually assigned chemical, biological or physical properties. Model benthic organisms are introduced in the form of automatons, i.e. programmable entities, that are capable of moving through the particle lattice by displacing or ingesting-defecating particles. Each automaton obeys a set of rules, both deterministic and stochastic, designed to mimic real organism behavior, with different types of organisms having different sets of rules.

This project involves myself, two post-doctoral fellows, i.e., Dr. Filip Meysman (NIOO, The Netherlands) and Dr. Jae Choi (Dalhousie), and a Ph.D. graduate student, Daniel Reed.

WORK COMPLETED

Work in this fiscal year centered on 1) adding a new functional class of organisms to the LABS model (Choi) and 2) evaluating the meaning of previous results from LABS with small deposit-feeding organisms only (Meysman). Dan reed was charged with completing his statutory course work and passing his comprehensive examination, which he did on 6 September 2002. He has now begun a study of the effects of mixing in LABS on different half-lived tracers and its meaning to "agedependent" mixing. The project has published two papers (C&G 2002, JMR 2001), and has recently submitted 2 others to the Journal of Marine Research.

RESULTS

1) Head-Down Deposit Feeders: Adding a Functional Class to LABS

The initial version of our lattice-automaton biotubation simulator, LABS, contained only one type of organism, i.e., a small deposit feeder, similar to a Capitelid. We have expended considerable energy to introduce another functional class. We chose a head-down deposit feeder. The activities of this second class of head-down deposit feeding organisms have been integrated into the Fortran 90/95 code using the same approach as that which had been developed for the first class of general, worm-like organisms. This integration was accomplished by: (1) the generalisation of the low-level algorithms of colonisation, death, locomotion, head-movement, ingestion, egestion; (2) the segregation of higher-level rules to a small set of organism-specific routines; and (3) the allotment of a greater degree of user-definable constraints, in the form of a parameter list, determined at run-time – see Fig. 1. The development of this new functional class of organisms will be the basis for much of our research in the comming year.

2) Diffusion and the LABS Model

When dealing with bioturbational effects on tracers and other particle-specific compounds in sediments, the vast majority of investigators use a diffuson model to interpret their distributional data. How does the LABS model (and its results) relate to the diffusion model? Secondly, if one laterally averages the 2-D results from LABS, the resulting tracer profiles "look" diffusive and can be interpreted as such, even though the automatons are involved in non-local mixing through feeding and defecation. Why is this the case? We have directed some of our research energies at answering these question because wide acceptance of LABS will not be possible unless potential users see the tranparent link between past results and future results with LABS.

LABS is a highly generalized mechanistic description of sediment mixing. Diffusion is a highly idealized non-mechanistic description of the effects of bioturbation. Other models, like tansition matrix descriptions (Shull, 2001, L&O), functional biodiffusors (François et al., 1997, Acta Biotheor.), and non-local 1-D models (Boudreau, 1986, 1987, Am. J. Sci.) also describe sediment mixing. How are all these models and their results related? We analyzed how these models are mathematically related and what assumptions must be made in order to transform one model into another; our result is the classification in Table 1 (Meysman et al., 2002a, submitted to JMR).

We have found that all currently available models are related through three properties and related criteria, i.e., frequency, symmetry and scale of the mixing motions. In addition we have shown that non-local models have a natural diffusive equivalent that explains why their predicted tracer profiles "look" diffuive.

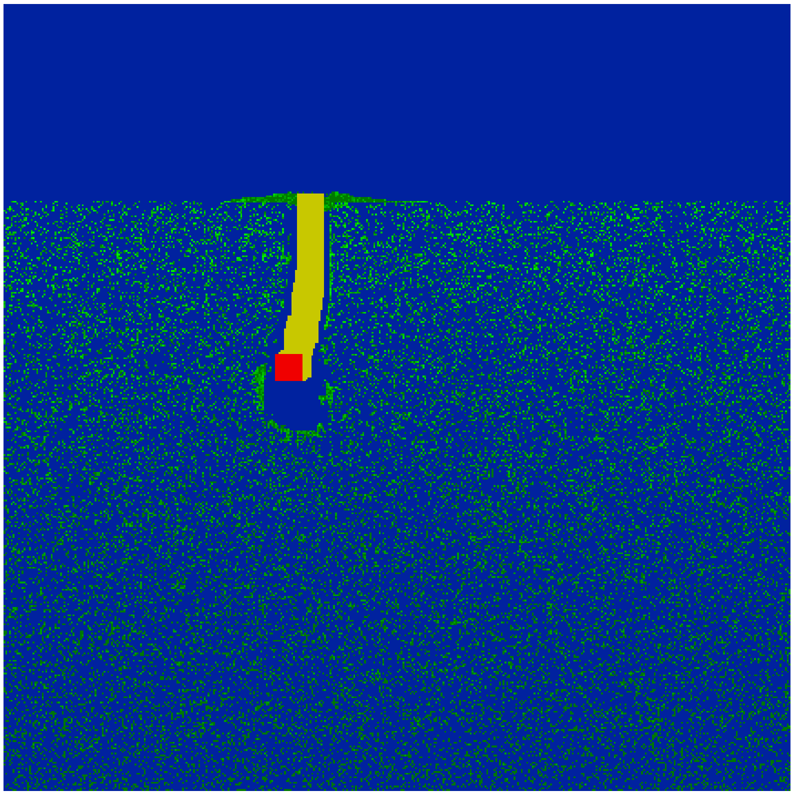

Figure 1. Visualization of a head-down deposit-feeding automaton. This image is 4 "days" into the simulation as the animal first creates its burrow. The red square is the animal's head, and a mound is building at the posterior end at the sediment-water surface. The organism's dimensions are: 0. 5 cm wide X 4 cm long. The model dimensions are: 15 cm X 15 cm.

Table 1. Classification of models for sediment mixing, based on the nature of the mixing (local versus nonlocal) and the mode of representation of the sediment or actions of the organims (discrete versus semi-continuous versus continuous). LABS is a discrete nonlocal model, whereas diffusion is a continuous local model.

	discrete	**semi-continuous**	**continuous**
local	I Isotropic Random walk	II Biodiffusor (functional approach)	III Biodiffusion
non-local	IV Transition matrix	V Functional approach	VI Exchange function

Secondly, we have been able to construct a laterally-averaged analytical model of a 1-D automaton that resembles our LABS creatures (Fig. 2A)., in which we only model its feeding-defecation behaviour. The results of these 1-D simulations are illustrated in Fig. 3 for the steady state distribution of ^{210}Pb. Large organisms with sharp feeding and defication functions (distances) are predicted to create ^{210}Pb distributions that are "wavy" and quantitatively different than diffusion profiles. (In nature the former may be difficult to observe because of the coarse resolution of current isotopic methods.) Only when the organisms become small and or have sloppy defecation functions do the profiles look diffusive.

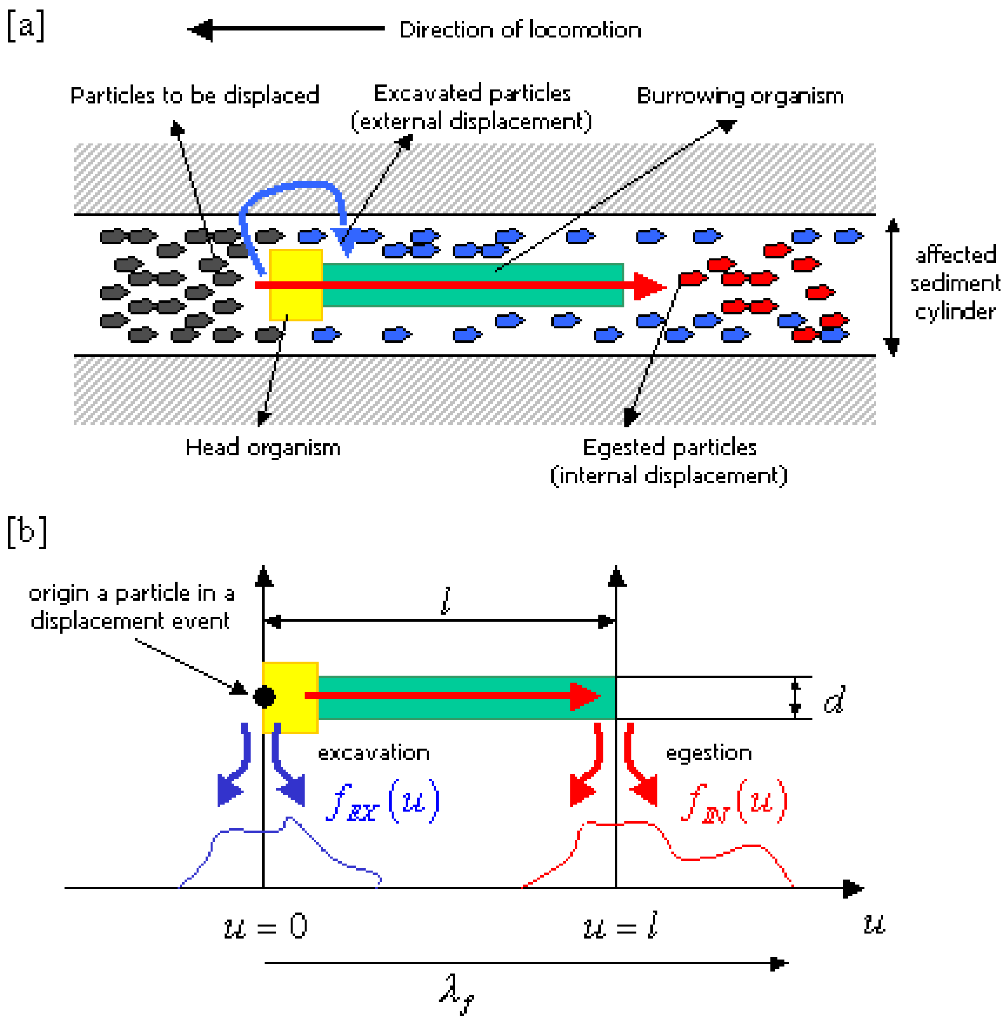

Figure 2. Top diagram: schematic representation of small deposit feeder as in our one-dimensional continuous model equivalent to the LABS model. The organism eats at its head and defecates at the rear end and moves up and down the sediment column at a prescribed rate. Bottom diagram: illustration of general feeding and defecation functions for this organism.

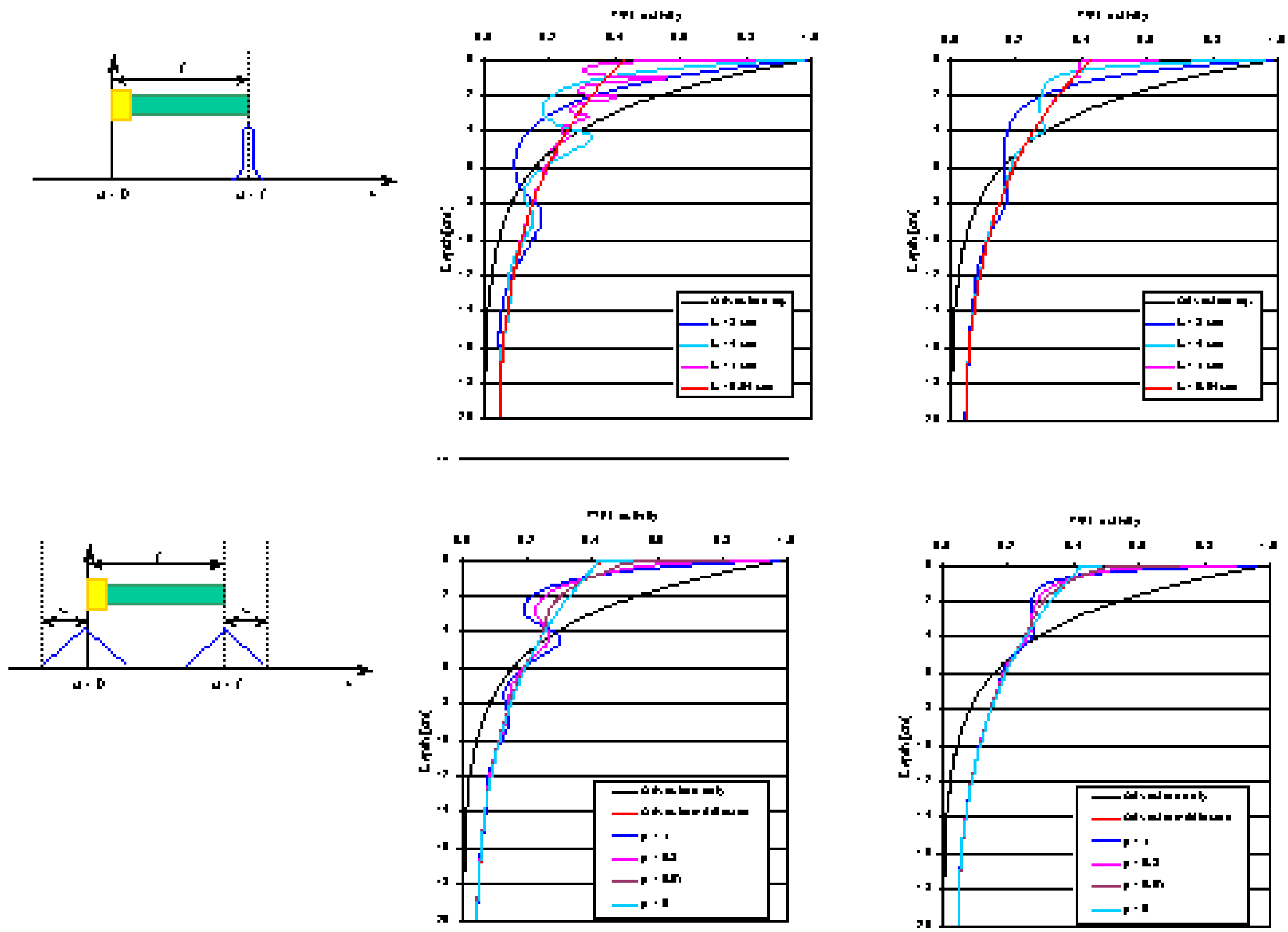

Figure 3. Steady-state ^{210}Pb profiles generated by organisms with the feeding-defecation functions in the left-hand diagrams. The cuves in the plots correspond to different sized organisms, and a diffusion-advection model curve is included for reference.

IMPACT/APPLICATIONS

LABS and our related analyses have the potential to alter our understanding of mixing of sediments and to make **predictions** that can be tested. For example, we have shown above in Fig. 3 that if the mixing is not truly diffusive, then there is the possibility of seeing wave-like distributions of travers and that the near-surface behaviour of tracer concentrations is very different with non-diffusive mixing. The community is being provided with a fundamentally different tool than it has had until now, and much will be discovered.

TRANSITIONS

Our NICOP partners, Peter Jumars and Larry Mayer are now planning to use LABS and will be sending a student to learn its functioning.

RELATED PROJECTS

Larry Mayer and Peter Jumars at the Darling Center are collecting data we can use to extend the model, including transformation of sediments by passage through an animal's gut.

PUBLICATIONS

Choi, J., François-Carcaillet, F. and Boudreau, B.P. (2002) Lattice-automaton bioturbation simulator (LABS): Implementation for small deposit feeders. Computers and Geosciences 28, 213-222.

Boudreau, B.P., Choi, J. and François-Carcaillet, F. (2001) Diffusion in a lattice-automaton model of bioturbation by small deposit feeders. Journal of Marine Research 59, 749-768.

Meysman, F.J.R., Boudreau, B.P., and Middelburg, J.J. (submitted) Relations between local, non-local, discrete and continuous models of bioturbation. Journal of Marine Research (July 2002)

Meysman, F.J.R., Boudreau, B.P., and Middelburg, J.J. (submitted) Why does biological mixing resemble Fickian diffusion? Journal of Marine Research (July 2002)